Energy & Buildings 169 (2018) 127–140

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy poverty methodology based on minimal thermal habitability conditions for low income housing in Spain

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A R T I C L E I N F O

Article history:
Received 7 August 2017
Revised 7 March 2018
Accepted 11 March 2018
Available online 21 March 2018

Keywords:
Energy poverty
Housing stock
Spain
Low income households
Energy consumption
Adaptive comfort

A B S T R A C T

Energy poverty affects an increasing number of households in the European Union. It is urgent the development of definitions and methods adapted to regional conditions that gather important housing construction and climatic differences between Northern and Southern countries beyond different income levels. Mainstream energy poverty methods are focused on heating requirements influenced by health risks derived from living in cold homes. However, the evaluation of energy poverty in warmer climates must also consider health impacts related to households' exposure to indoor overheating and consequent cooling needs that will likely be exacerbated by temperature increase due to climate change.

The present research is aimed at developing a method for evaluating energy poverty in low income dwellings adapted to the Spanish context that gathers climatic, building and socioeconomic particularities of the country. The research was conducted through the evaluation of three representative social housing blocks of vulnerable households located in three different climates and regions. The proposed method is focused on the energy expenditure required to achieve minimal thermal habitability conditions in low income dwellings. Hence, both heating and cooling needs are appraised according to adaptive comfort criteria.

The resulting method constitutes a useful tool for the identification of households suffering from energy poverty as well as the degree of the need they require (Fig. 1). Finally, the method poses an aid in the decision-making processes related to dwelling energy retrofitting actions and policy development.

1. Introduction

1.1. Relevance of research

Updated Eurostat data reveals that 9.4% of the total population of the European Union is unable to keep their home adequately warm and 9.1% present arrears on utility bills [1]. These worrisome data outline a problem that has started to be addressed in EU agenda within recent years. Some directives urging Member States to define their vulnerable citizens can be found as well as others supporting investments to tackle energy poverty [2–6]. In line with these directives, several European Commission working documents and reports have arisen proposing definitions, recommendations and possible solutions towards the eradication of energy poverty [7–9]. The European Parliament has claimed the Commission and Member States the development of policies to fight the problem through several resolutions [10–12].

Energy poverty concept was first developed in UK during the energy crisis of 1970′ and the definition and corresponding measurement has evolved over the years to adequately identify and face the problem in the country. Current European political context urge Member States to develop their own energy poverty methodologies but existing regional differences amongst countries must be considered weighting the suitability of mainstream definitions and gathering local climate, building and socioeconomic particularities. Special attention must be paid to climate differences in Southern countries where overheating and consequent cooling needs must be incorporated in the equation of energy poverty. In addition, the delimitation of the problem should go hand in hand with housing retrofitting guidelines, as it has been widely recognised as the only effective long-term solution to energy poverty.

1.2. Aims and objectives of the study

This paper aims to develop a new method for evaluating Spanish households energy poverty conditions that gathers climatic, building and socioeconomic particularities of the country.

This method must be useful in the first place, not only for the identification of the fuel poor but also for establishing households'

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https://doi.org/10.1016/j.enbuild.2018.03.038
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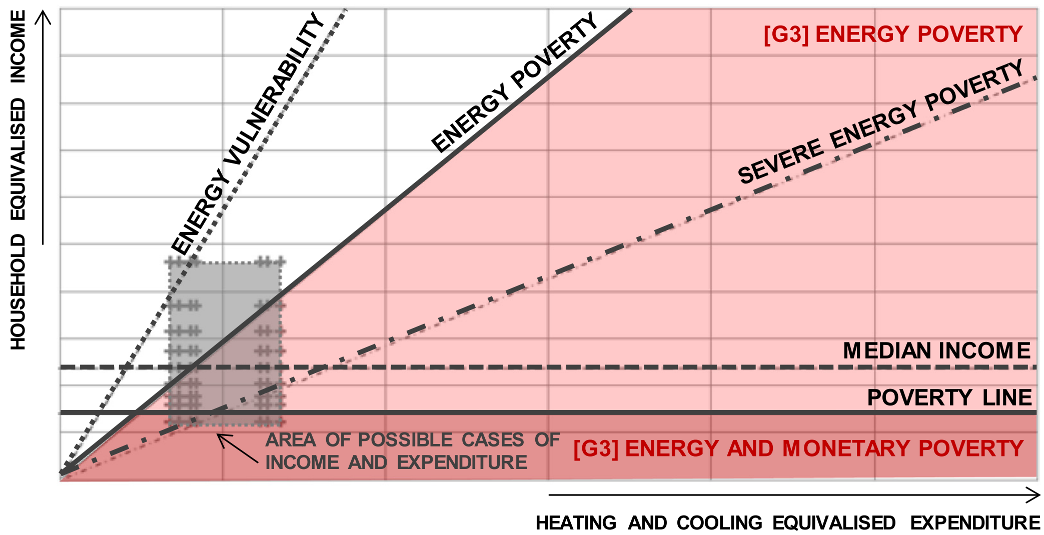


Fig. 1. Spanish households energy poverty evaluation chart.

degree of need. In the second place, the method must contribute to the decision-making process related to dwelling energy retrofitting so as to establish priority household target groups as well as to determine the type of intervention required.

To achieve the main objective of the research, the following objectives are attained:

- To determine households' energy costs to obtain required heating and cooling energy needs for minimal indoor thermal habitability conditions.
- To establish new energy poverty thresholds for the Spanish context.
- To delimitate those households most in need and their specific requirements.

2. The evaluation of energy poverty

2.1. Measurement of the problem

The concept of fuel poverty, as it was named in the beginning, arises as an answer to the fuel crisis of 1973 when the phenomenon shifts from a marginal problem related to poverty to a wider matter studied by researchers as a specific problem. Many researchers study the phenomenon in UK between 1970′ and 1980′ [13,14] and in 1991 Brenda Boardman establishes a preliminary definition that is still in force [15]. After several recognitions of the problem by UK Government [16,17], in 2001 UK Government formulates its methodology to measure fuel poverty, following Boardman's criteria:

> *A household is said to be in fuel poverty if it needs to spend more than 10% of its income on fuel to maintain an adequate level of warmth (usually defined as 21 degrees for the main living area, and 18 degrees for other occupied rooms)* [18].

These temperatures are based on recommendations made by the World Health Organization [19]. The Fuel Poverty Ratio is defined as:

$$Fuel\ Poverty\ Ratio = \frac{fuel\ costs\ (usage\ x\ price)}{income}$$

This first official methodology has been revised and fuel poverty in England is currently monitored using the *Low Income High Energy Costs (LIHC)* indicator [20,21] in which:

> *A household is considered to be fuel poor if: a) they have required fuel costs that are above average (the national median level), b) were they to spend that amount, they would be left with a residual income below the official poverty line.*

After first methodological developments in UK, there was a willing of quantifying fuel poverty in the rest of European countries. However economic, social and climatic differences across Europe prevented extrapolating the income and expenditure approach. As a consequence of this limitation, years later the *consensual* approach was developed based on European Community Household Panel data [22]. Fuel poverty was characterised by means of subjective indicators as the inability to afford to heat home adequately, inability to pay utility bills on time or the lack of adequate heating facilities and objective indicators such as the presence of damp walls and/or floors, the lack of central heating and the existence of rotten window frames. These indicators where combined into composite indicators enabling cross country comparisons. As an example, one of composite indicators was as follows:

$$0.33\delta + 0.33\lambda + 0.33\mu$$

Where only the three values considered as objective indicators are weighted: presence of damp walls and/or floors (δ), the existence of rotten window frames (λ) and the lack of central heating (μ). First studies showed the highest rates of fuel poverty in Southern countries: Greece, Spain and Portugal [23]. This methodology is still used for cross-country analysis and recent results showed Eastern newer Member States facing worst levels of fuel poverty followed by Southern countries where fuel poverty prevalence is still remarkable [24].

2.2. Urgent need for new definitions

Besides mainstream methodologies to quantify *energy poverty* the income and expenditure approach and the consensual approach, some European countries have started developing their own definitions and methodologies. That is the case of Ireland, where the Government launched their *Warmer Homes – A Strategy for Affordable Energy in Ireland* in which:

> *A household is unable to attain an acceptable level of energy services (including heating, lighting, etc.) in the home due to an inability to meet these requirements at an affordable cost* [25].

Where the affordable cost is fixed at the 10% of income till more precise evaluation studies are conducted. France has also officially recognised the existence of what they have named energy precariousness in 2010 under the Grenelle Law [26] considering:

A person in a situation of energy precariousness if his household presents specific difficulties to have required energy supply to satisfy its basic needs due to poor resources or habitability conditions [26].

Efforts of this country towards the eradication of the problem are remarkable, as the creation of the French Energy Precariousness Observatory in 2011. Recent research has shown the importance of clustering households characterising the energy consumption according to socio-economic, dwelling and regional characteristics [27], the need of a method to evaluate energy consumption [28] and problems related to the application of the LIHC indicator with real households costs given the lack of estimated costs data. Finally, Romania has set its first steps towards an energy poverty definition [29].

Despite the lack of new definitions and methodologies in the rest of the countries, many attempts to locally understand the problem can be found: in Austria, a study analysed the situation of households in or at risk of poverty or suffering from energy poverty in Vienna [30], in Italy another study focused on the affordability of energy [31], in Belgium, the Centre d'Etudes Economiques et Sociales de l'Environment is carrying out this analysis [32] or the Greek studies that relate household socioeconomic situation with housing conditions and the affordability of energy services [33,34]. Along with these studies, some research has defined a new type of energy poverty suffered in Eastern Post-communist countries in which households living in social housing connected to district heating do not experience cold temperatures but are unable to pay energy bills [35,36]. Additionally, researchers have tried to measure the problem through mainstream methodologies, as the implementation of subjective and objective approach in Greece [37] or the evaluation of the impact of using different energy poverty lines in Germany [38]. Finally, some methodological proposals can be found as the Fuel poverty risk index developed for Italy that correlates energy poverty conditions with building energy performance [39] or the methodology to assess the potential energy poverty developed for Portugal [40]. It is expectable that the recently created EU Energy Poverty Observatory [41] will pose a ground-breaking advance in the delimitation and characterisation of the problem.

In Spain, energy poverty concept is yet to be officially defined and recognised. Nevertheless, numerous studies have arisen demonstrating the existence of the problem in the country. First reference to energy poverty can be found in 1989 when families that lived in huts were re-housed and declared being unable to afford energy bills. Since that time there are no more references to energy poverty in Spain till first European cross country analysis developed by Healy [42]. Later on, studies have been focused on the evaluation of the problem by means of existing methodologies: the consensual and the income and expenditure approach [43–45].

Along with national scale studies, some regional analysis has been conducted as the one carried out for Aragon where qualitative and quantitative analyses were used [46] or the analysis for the Autonomous Region of Madrid [47]. Furthermore, some cities and provinces have developed their own energy poverty reports in order to take action to fight energy poverty as Valencia [48], Madrid [49], Guipuzcoa [50].

Main conclusions of these studies point at the limitations of using the income and expenditure approach due to the lack of data related to households' required energy costs given that current official statistics only gathers households' real energy expenditure. Some of these analyses also claim the high degree of subjectivity of the indicators used in the consensual approach generating in some cases contradictory results in energy poverty rates [44,51].

Fig. 2. Autonomous Regions and province capitals selected for the study.

3. Materials and methods

3.1. Geographic scope and case study selection

This study was intended to develop a method for appraising households' energy poverty conditions in Spain incorporating climatic, building and socioeconomic particularities of the country. On this basis, representative social housing blocks located in three capital provinces from three different Autonomous Regions were selected as study cases: Ávila, from Castile and Leon, Madrid, from the Autonomous Region of Madrid, and Sevilla, from Andalusia (Fig. 2).

(a) First, regarding climatic conditions, the whole range of climatic conditions that can be found within the country was considered. Spanish Building Technical Code (Código Técnico de la Edificación – CTE by its initials in Spanish) classifies weather conditions according to winter severity, with ranges from A for those regions with mild winters to E for the most severe conditions, and summer severity, that goes from 1 for the coldest regions to 4 for the warmest summers, as shown in Fig. 3 [52]. Ávila holds the highest winter severity (E1), Madrid presents an intermediate weather (D3) and Sevilla has the highest summer severity (B4). Weather data from selected cities is outlined in Table 1.

(b) Socioeconomic inequalities were considered and calculated through Autonomous Region available data, given official national statistics breakdown. AROPE indicator is defined as the share of population in at least one of the following three conditions: at risk of poverty, meaning below the poverty threshold (60% of the median income), in a situation of severe material deprivation (people who cannot afford at least four of a total of nine items) and people living in a household with a very low work intensity [6]. According to this indicator Andalusia presents the highest share of population in need (38.4%), Castile and Leon levels are close to national average value (22.3%) and the Autonomous Region of Madrid is one of the wealthiest regions of the country (18.6%) as plotted in Fig. 4.

(c) Building particularities were gathered as well by selecting representative social housing where vulnerable households are likely to live, according to the Spanish Vulnerable Neighbourhood Catalogue [56]. Urban developments built between

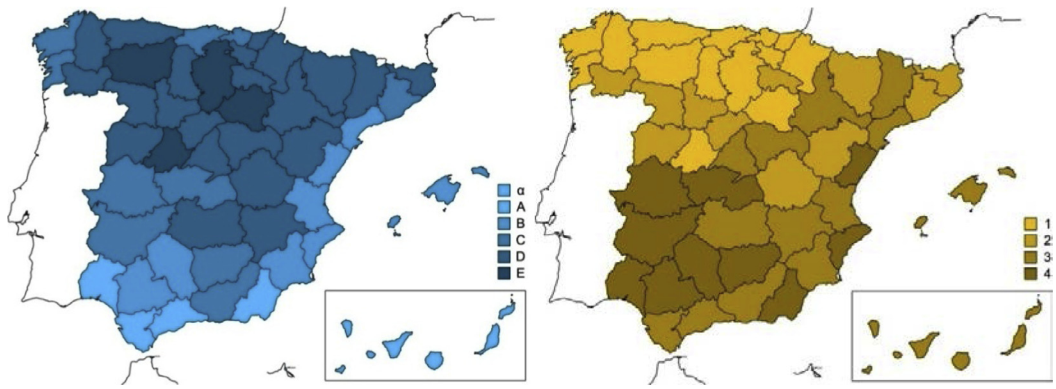


Fig. 3. Spanish winter severity (left) and summer severity (right) by provinces [53].

Table 1
Weather data of selected cities [54].

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ávila	Mean temp. (°C)	3	4.3	6.7	8.5	12.5	17.4	20.6	20.2	16.5	11.4	6.4	4
	Maximum (mean) temp. (°C)	7.6	9.4	12.6	14.3	18.5	24.6	28.5	27.9	23.4	16.9	11.2	8.4
	Minimum (mean) temp. (°C)	−1.6	−0.8	0.8	2.7	6.4	10.2	12.6	12.4	9.6	5.9	1.7	−0.4
	Relative humidity (%)	78	72	63	63	59	51	43	45	56	69	78	79
Madrid	Mean temp. (°C)	6.3	7.9	11.2	12.9	16.7	22.2	25.6	25.1	20.9	15.1	9.9	6.9
	Maximum (mean) temp. (°C)	9.8	12	16.3	18.2	22.2	28.2	32.1	31.3	26.4	19.4	13.5	10
	Minimum (mean) temp. (°C)	2.7	3.7	6.2	7.7	11.3	16.1	19	18.8	15.4	10.7	6.3	3.6
	Relative humidity (%)	71	65	55	56	53	44	38	41	50	64	71	74
Seville	Mean temp. (°C)	10.9	12.5	15.6	17.3	20.7	25.1	28.2	27.9	25	20.2	15.1	11.9
	Maximum (mean) temp. (°C)	16	18.1	21.9	23.4	27.2	32.2	36	35.5	31.7	26	20.2	16.6
	Minimum (mean) temp. (°C)	5.7	7	9.2	11.1	14.2	18	20.3	20.4	18.2	14.4	10	7.3
	Relative humidity (%)	71	67	59	57	53	48	44	48	54	62	70	74

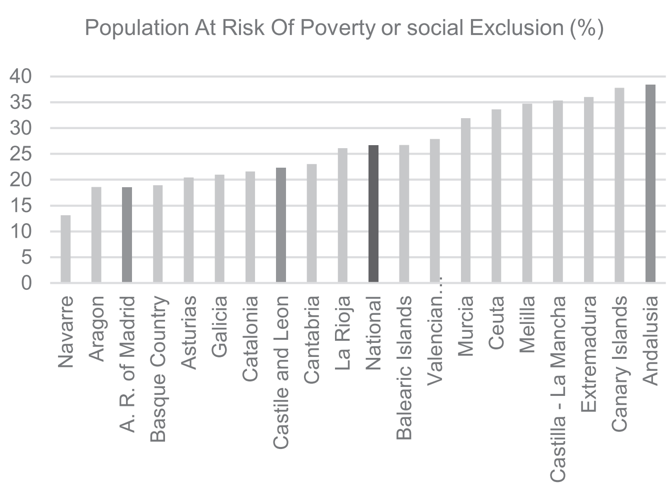


Fig. 4. Population at Risk of Poverty or social Exclusion according to Europe 2020 by Autonomous Region is Spain [55].

1960 and 1975, before the introduction of the first Spanish Thermal Regulation [57], represent 17.63% of all vulnerable neighbourhoods. The most representative archetype in those years was the linear block. The selected blocks, presented in Table 2, consist of four to five storeys where each staircase connects two dwellings in each floor. Dwelling floor areas range from 45 to 60 m^2. Thermal construction properties are shown in Table 3.

3.2. Heating and cooling energy expenditure

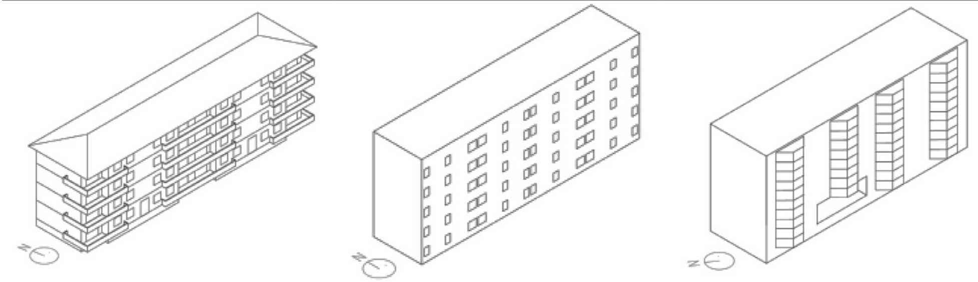
First part of the study consisted on delimitating heating and cooling energy expenditure. Previous research has demonstrated shortfalls associated with the use of official statistics in order to evaluate households expenditure given that official databases gathers real expenditure instead of required expenditure [58]. That is why, a specific method to establish energy costs was set as follows:

(a) Dwelling thermal performance was simulated with software Energy Plus 8.1. [59]. *Spanish Weather for Energy Calculations* – SWEC database [60] was used for the city of Ávila and *International Weather for Energy Calculations* – IWEC database [61] for the city of Madrid and Seville. The study focused on dwellings energy performance as the evaluation of households' conditions was the final objective. The most representative dwellings were selected from each block, according to their relative position within the building, resulting into nine flats per building as shown in Fig. 5. Occupational patterns were set according to those used in the Spanish Technical Code criteria to evaluate Spanish building energy ratings [52]. Thus, internal gains were broken down into occupancy, equipment and lighting. Minimal ventilation rates were set following indoor thermal quality requirements of Spanish Technical Code requirements [52] and infiltration rates were set based on the Annex II of Manual of Technical Basis for existing building energy rating [62]. Finally, night summer ventilation was considered as established in Spanish Energy Rating software. All these values are shown in Table 4.

(b) Heating and cooling energy required to achieve minimal thermal habitability conditions in dwellings was set through the *adaptive demand* calculation [63,64]. The concept of adaptive demand is based on adaptive model from ASHRAE 55-2013 with some corrections made for its application in domestic spaces. The interest of using this standard, and hence the adaptive demand, for the evaluation of energy

Table 2
Selected linear building blocks.

Ávila	Madrid	Sevilla



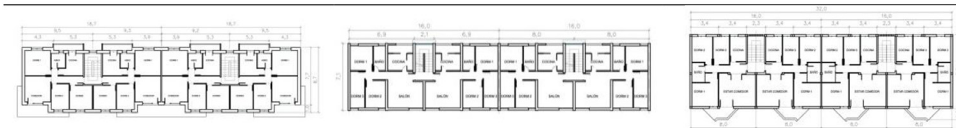


Table 3
Thermal construction properties of studied blocks.

	Ávila		Madrid		Seville	
	[W/m² K]	[kJ/m² K]	[W/m² K]	[kJ/m² K]	[W/m² K]	[kJ/m² K]
Walls	1.33	114.15	2.38	199.15	1.7	57.25
Flat roof	–	–	2.18	142.72	2.18	142.72
Pitched roof	1.96	81.5	–	–	–	–
Floor under pitched roof	2.37	136.9	–	–	–	–
Floor	2.37	137.65	2.12	144.63	2.37	137.65
Ground floor	2	189.45	–	–	–	–
Ground floor with air chamber	–	–	2.82	144.62	2.82	144.62
Windows (glazing/frame)	5.78/5.26		5.78/5.26		5.78/5.26	
Internal partitions	2.29	33.13	2.29	33.13	2.29	33.13
Dwelling internal partitions	1.84	60.2	2.023	195.02	1.84	60.2

Table 4
Occupational patterns considered for dwellings [52].

		Hours						
		1–7	8	9–15	16–18	19	20–23	24
Sensible occupancy (W/m^2)								
	Workday	2.15	0.54	.54	1.08	1.08	1.08	2.15
	Weekend	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Latent occupancy (W/m^2)								
	Workday	1.36	0.34	0.34	0.68	0.68	0.68	1.36
	Weekend	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Lighting (W/m^2)								
	All days	0.44	1.32	1.32	1.32	2.20	4.40	2.20
Equipment (W/m^2)								
	All days	0.44	1.32	1.32	1.32	2.20	4.40	2.20
Summertime ventilation (ach/h)	4.00	4.00	*	*	*	*	*	
All year ventilation	*	*	*	*	*	*	*	

*For summertime a night ventilation of 4 ach/h are considered between 1 and 8. Rest of the time air changes per hour will be the minimum required by Spanish Technical Code, around 5 l/s per person.

Table 5
Comfort temperature boundaries adjustments for night time hours.

	Metabolic rate			Clothing level			Final temperature adjustment[a]
	Daytime	Night time	Temperature adjustment	Daytime	Night time	Temperature adjustment	
Underheated season	1–1.3 met	0.8 met	+0.2 °C	0.5–1 clo	1.5 clo	−3 °C	**−2.8 °C**[a]
Overheated season	1–1.3 met	0.8 met	+0.2 °C	0.5–1 clo	0.3 clo	+1.2 °C	**+1.4 °C**

[a] Comfort temperatures adjustments for the underheated season were limited to 16 °C in line with studies that point this temperature as the threshold for respiratory diseases [65].

Table 6
Households' heating systems distribution of all households with any kind of heating system (%).

	Castile and Leon	Autonomous Region of Madrid	Andalusia
Individual electric boiler	1.74	8.56	10.69
Electric radiators	7.12	8.21	43.77
Under-floor heating	0.41	0.01	0.53
Central gas heating	7.88	16.75	1.35
Individual gas boiler	32.99	53.98	2.71
Gas bottles	0.95	0.12	1.35
Piped heat pump	0.37	1.21	1.63
Not piped heat pump	0.11	1.36	5.81
Individual diesel boiler	22.49	0.88	4.31
Central diesel heating	12.52	7.69	1.61
Coal central heating	1.03	0.52	0.00
Wood	5.11	0.05	2.12
Other	7.26	0.66	24.11

Table 8
Income decile levels by region [69].

	Castile and Leon	Autonomous Region of Madrid	Andalusia
D1	6056	6642	4764
D2	7857	9144	6144
D3	8880	10,373	7333
D4	10,188	13,192	8,571
D5 (median income)	11,824	14,406	9,714
D6	13,600	17,096	11,200
D7	15,750	19,680	13,452
D8	18,400	22,288	14,170
D9	23,160	28,088	21,336
D10	52,666	99,804	82,104

poverty conditions is that it reflects occupants' ability to adapt to climate, so it enables considering Spanish climatic diversity. Furthermore, widest comfort ranges set in the standard have demonstrated to be closer to occupants' expectations. The *adaptive demand* comfort temperature ranges are based on ASHRAE 55-2013 boundaries for the 80% of acceptability calculated from a neutral operative temperature (T_{ot}) based on monthly mean external temperature (T_o):

$$T_{ot} = 0.31T_o + 17.8$$

Besides the above, the adaptive demand introduces some adjustments for sleeping hours given that it assumes some clothing and metabolic variations. These modifications of clothing and metabolic values are shown in Table 5 along with resulting adjustments admitted in temperature ranges.

(c) Next step consisted on calculating the energy consumption derived from the adaptive demand. Information related to the type of heating and cooling systems used by region was extracted from the Households and Environment survey [66]. Table 6 shows heating systems distribution for those households with any kind of heating system. The individual gas boiler is the most common heating system in Castile and Leon and the Autonomous Region of Madrid while the electric radiators are the most frequent in Andalusian dwellings. Individual splits were considered as the most prevalent cooling systems across regions.

Efficiency of heating and cooling systems shown in Table 7 was estimated according to Spanish Energy Rating procedure for existing buildings [67].

(d) The final step to set households 'energy expenditure consisted in applying energy prices from Eurostat database according to energy source considered in each case. These values were 0.054 €/kW h for gas and 0.1851 €/kW h for electricity [68].

3.3. Income levels

After determining energy expenditure, second part of the study consisted of establishing households' income levels with data obtained from the Spanish Family Budget Survey [69]. Income deciles were calculated for the three autonomous regions studied as plotted in Table 8. This enabled considering the whole range of households' income.

Besides households' income estimation, previous research has revealed the existing relationship between monetary and energy poverty [58]. Therefore poverty thresholds were calculated according to Eurostat as the 60% of the median equivalised income and incorporated in the developed energy poverty method.

3.4. Heating and cooling energy poverty thresholds

Traditional energy poverty threshold fixed in the 10% was considered adequate at this stage, in line with previous research developed in the country [44,51]. However this percentage is referred to all households' energy needs which means that besides heating and cooling expenditure, it gathers dwelling hot water, lighting, cooking and appliances. This research focused on the delimitation

Table 7
Efficiency of heating and cooling systems.

	Heating		Cooling	
	Equipment	Seasonal performance value	Equipment	Seasonal performance value
Ávila	Individual gas boiler	75	–	–
Madrid	Individual gas boiler	75	Individual split	138.6
Sevilla	Electric radiators	95	Individual split	129.6

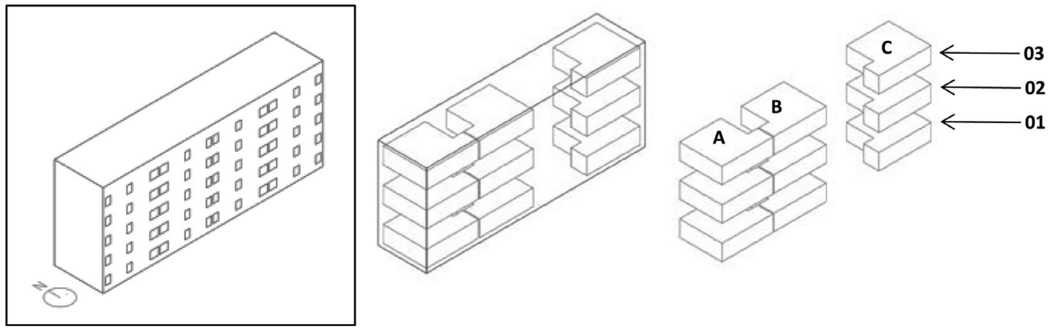


Fig. 5. Scheme of the nine representative flats selected from each linear block analysed.

Table 9
Energy costs distribution by region and energy poverty thresholds.

	Energy costs distribution (%)						Thresholds definition		
	Heating	Cooling	DHW	Cooking	Lighting	Appliances	Fuel poverty	Fuel vulnerability	Severe energy poverty
Ávila	33.2	1.4	10.4	13.4	5.3	36.2	3.5	1.75	7
Madrid	33.2	1.4	10.4	13.4	5.3	36.2	3.5	1.75	7
Seville	43.1	1.2	20.6	2.2	6	27	4.4	2.2	8.8

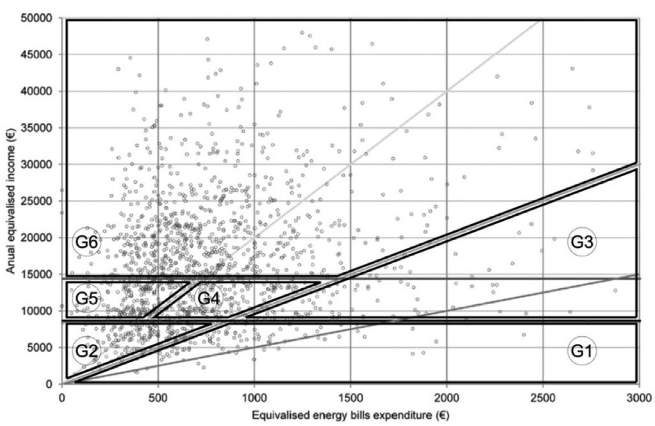


Fig. 6. Households division into groups according to fuel and monetary poverty thresholds [58].

of minimal thermal habitability conditions that should be achieved in dwellings so as to establish energy retrofitting priorities. Hence, the rest of dwelling energy services were considered out of the scope of this research. That is why new thresholds exclusively referred to heating and cooling needs were defined according to the middle household energy consumption share.

Data related to Spanish households' energy consumption from Spahousec project results was used for this purpose [70]. As reported in that project, energy consumption for different energy services varies by the three main climatic regions considered in it: North Atlantic, Continental and Mediterranean. Based on that data and taking into account the energy source and price for each case, the expenditure distribution was calculated for the three regions considered in this research.

3.5. Households groups

Last part of the research consisted of the analysis of household's relative position towards fuel and monetary poverty in order to understand the overlap between both problems and to establish priorities and intervention guidelines. Households were divided into groups according to different established thresholds, as conducted in previous research for the Autonomous Region of Madrid (Fig. 6) [58]:

Group 1 – Below both the monetary and the energy poverty line. Households in this group fall within both poverty types (energy expenditure and income levels).

Group 2 – Below the monetary poverty line but above the energy poverty line. This group consists of households whose income is less than 60% of median income.

Group 3 – Below the energy poverty threshold but above the monetary line. Formed by households whose expenditure on energy bills is above 10% of their income but whose income is more than 60% of median income.

Group 4 – Monetary and energy vulnerability: households whose income level is above the monetary poverty line but under the median income level, and whose energy expenditure is between 5% and 10% of their income. These households were considered vulnerable because an increase in their expenditure or a decrease in their income would place them below one of the two poverty lines.

Group 5 – Monetary vulnerability: these households' income is more than 60% of median income but below the median income line, and their energy expenditure is less than 5% of their income. These households could be considered vulnerable from a strictly monetary point of view.

Group 6 – Not vulnerable: this group is stable in terms of both monetary and energy expenditure, and distanced from vulnerable positions.

4. Results

4.1. Heating and cooling energy expenditure requirement

Results of heating and cooling energy consumption, based on adaptive demand are shown in Fig. 7. Important differences can be drawn from the evaluation of dwelling energy consumption in order to achieve minimal thermal habitability conditions. These contrasts are derived on the one hand from the climate where dwellings are located and on the other hand, from the relative position of the dwelling within the block. Climate impact on energy demand can be observed in dwellings located in Ávila where heating demand is four times the heating energy demand in dwellings from Seville. By contrast, in Seville cooling values are up

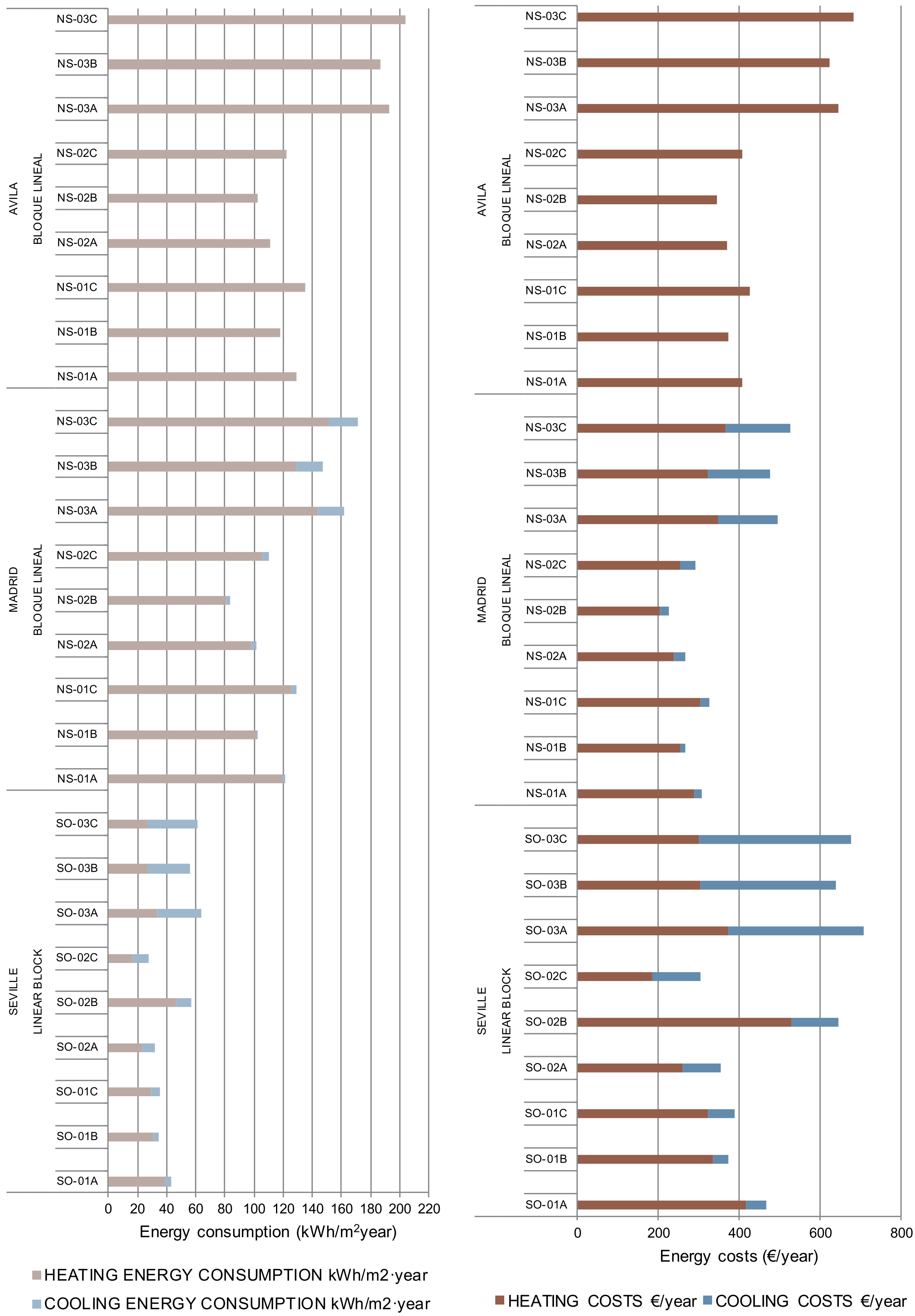


Fig. 7. Heating and cooling energy consumption (kW h/m^2) (left) and heating and cooling energy costs (€/year) (right).

to 30 kW h/m^2 while no cooling consumption is required in Ávila. Relative position of dwellings within the block also presents an important influence over energy consumption requirements. Top floors are the biggest energy consumers both for heating and cooling. Mid floor dwellings require the lowest rates of energy for heating while ground floor dwellings present better conditions for cooling energy consumption.

Results of dwellings energy expenditure are plotted in Fig. 7 along with energy consumption. The comparison of energy consumption with energy costs across dwellings show relevant

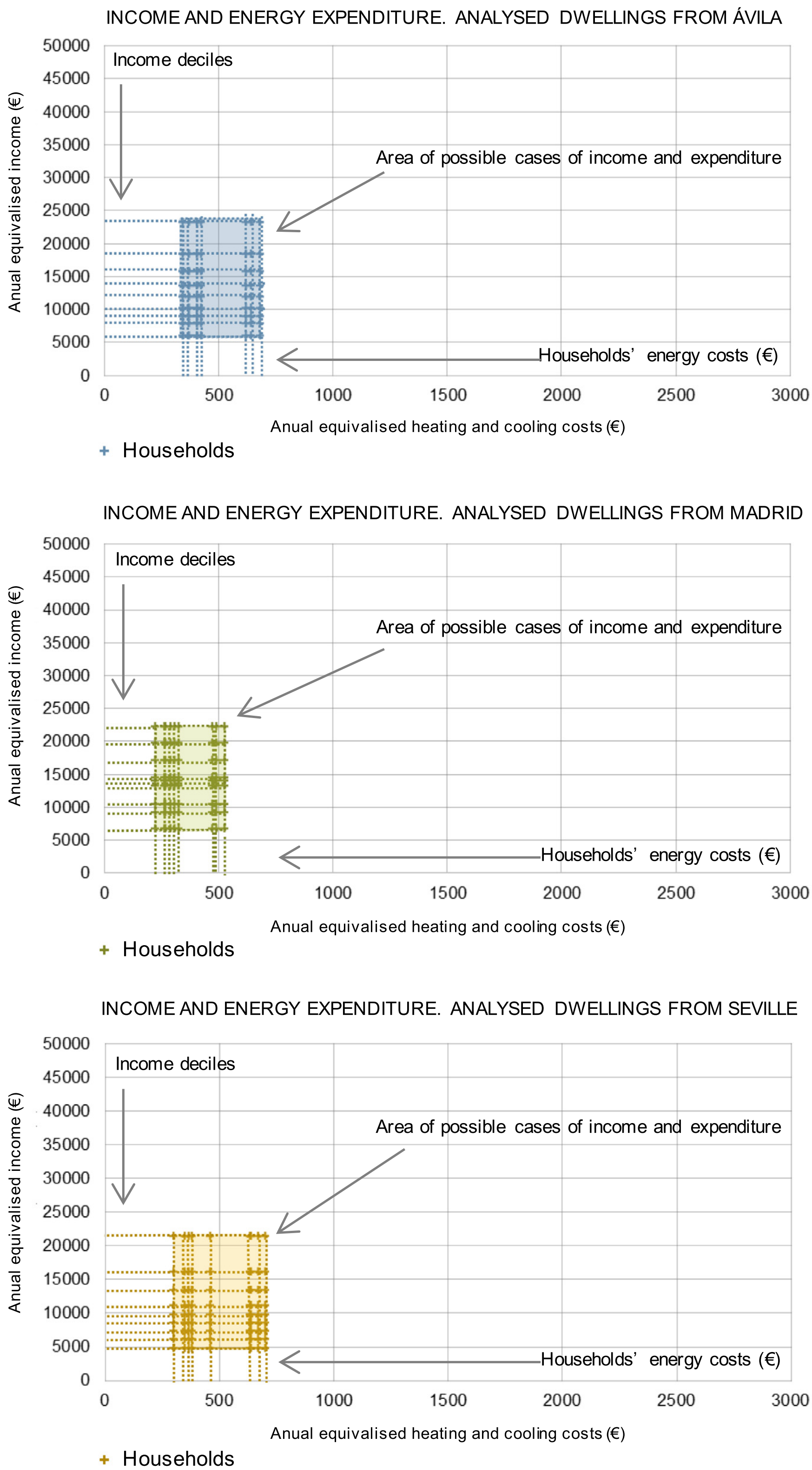


Fig. 8. Households' relative position regarding income and energy costs for analysed building blocks in Ávila (top), Madrid (middle), Seville (bottom).

findings. Heating and cooling expenditure in Seville dwellings can hit expenditure of those located in Ávila, even though energy consumption in Ávila is much higher. Electric heating radiators from Sevilla use a more expensive energy source than gas boilers located in dwellings from Ávila. This result goes in line with previous studies in which highest rates of households not being able to adequately heat their home in winter were found in Southern Spanish regions [45,51].

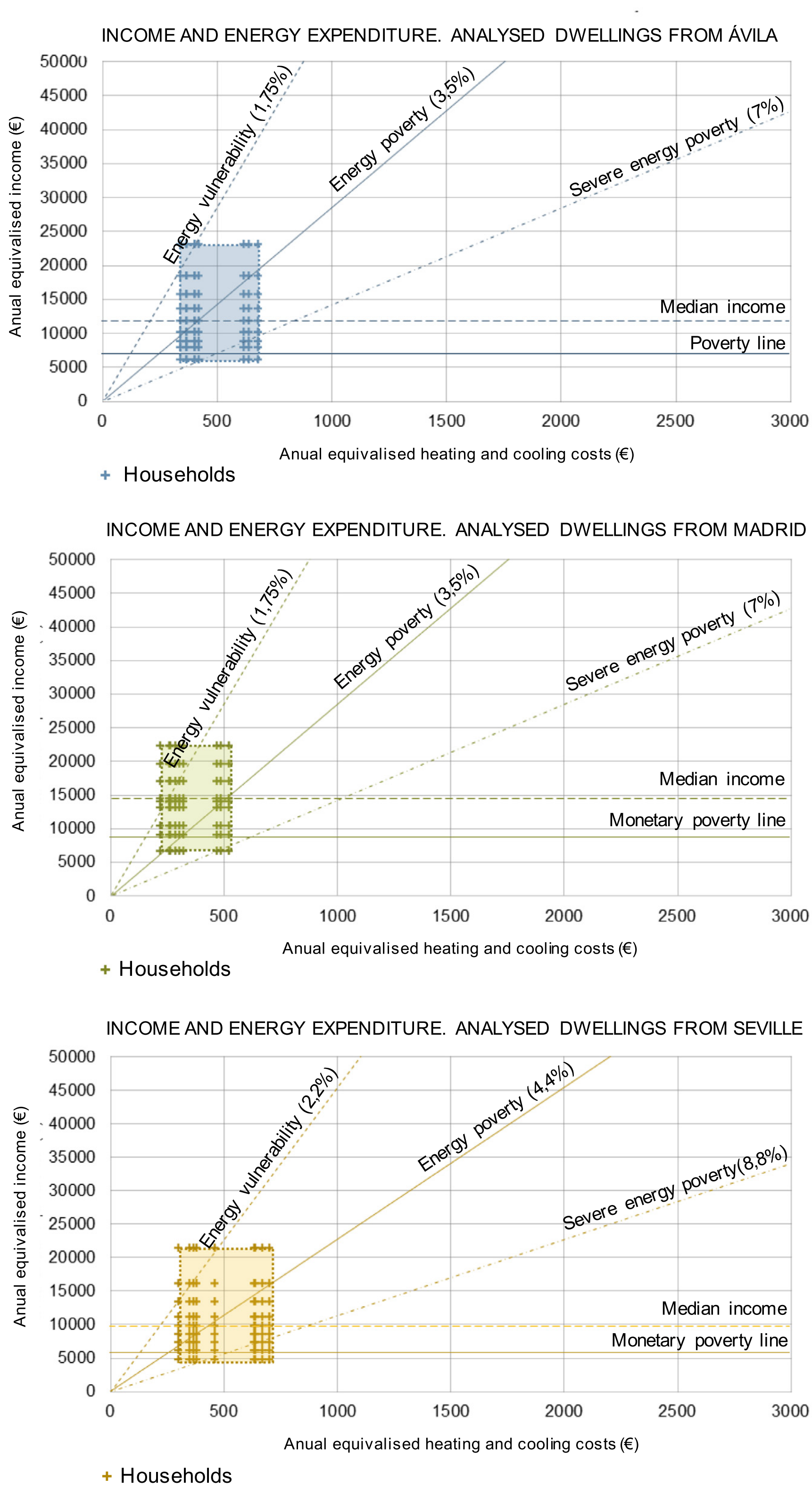


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Fig. 9. Energy poverty evaluation graph with the area of possible cases for housing blocks from Ávila (top), Madrid (middle) and Seville (bottom).

4.2. Households' income and energy costs: the area of possible cases of a building block

Energy cost results for studied dwellings (9 representative dwelling in each block) were combined with different income levels found for each region (9 income decile levels) to establish several hypotheses regarding possible household positions towards energy poverty. All these possible positions are delimitated within what was defined as the *area of possible cases* of a building block, plotted in Fig. 8 for each city and building block analysed. Dif-

ferences in relative positions and dimensions of the three rectangles can be observed. Rectangles from blocks located in Ávila and Seville present highest energy costs. In Ávila these high costs are caused by severe winter conditions and consequent high heating energy needs while in Seville these elevated costs are provoked by high electricity prices, which is the most common heating energy source. Besides that, the widest rectangle with the largest energy costs variability is the one from Seville, due to the elevated cooling needs of top floors that trigger energy consumption of those dwellings. Higher income levels from Ávila and Madrid Regions, make their respective rectangles be in higher positions in the graph.

4.3. Energy poverty thresholds

New energy poverty thresholds were set as a result of households' energy expenditure distribution of different energy services (Fig. 9). Energy poverty threshold for Castile and Leon and the Autonomous Region of Madrid was set in 3.5% while for Andalusia this value was fixed in 4.4%. In line with these values 'severe energy poverty' threshold was calculated as double the value of energy poverty baseline and 'fuel vulnerability' as half the value of energy poverty baseline. Dwelling energy costs distribution by autonomous region is shown in Table 9 as well as defined energy poverty thresholds.

These thresholds were incorporated to the energy poverty evaluation graph as can be seen in Fig. 9.

4.4. Household groups classification

Households were divided into groups according to their relative position towards thresholds established in the proposed energy poverty method, Fig. 10. In all cases households with the lowest income decile fall within Group 1, below both monetary and energy poverty line. Given housing parameters from the three cases analysed, households in Group 2, poor but with little heating and cooling expenditure, are almost non-existent. This is mainly because energy costs required for achieving minimal thermal conditions are high given the low energy efficiency of dwellings. An important number of households living in Ávila and Seville block would fall within Group 3, with incomes above monetary poverty line and with energy costs that go beyond the 3.5 and 4.4% respectively. The case of Madrid presents the largest number of households that would fall within Group 4, vulnerable towards both energy poverty and monetary poverty. A decrease in their income or an increase in energy prices would move these households to a position below either fuel or monetary poverty thresholds.

5. Discussion

The research conducted was intended to develop a new method for evaluating energy poverty in Spanish households, addressing country's particularities such as climate, socioeconomic characteristics and building particularities. To this end and based on an income and expenditure approach, the new method includes specific methodologies for the definition of each indicator gathered in it (Fig. 11).

The evaluation of households' energy needs and consistent energy expenditure was conducted by the utilisation of the adaptive thermal comfort criteria considered as the minimal thermal habitability conditions that should be guaranteed in energy poverty situations. This enabled incorporating an accurate evaluation of energy needs depending on the climate conditions considering householders adaptation abilities. Furthermore, the adaptive criteria facilitated the inclusion of overheating problems and cooling energy needs into the evaluation of energy poverty. Obtained from

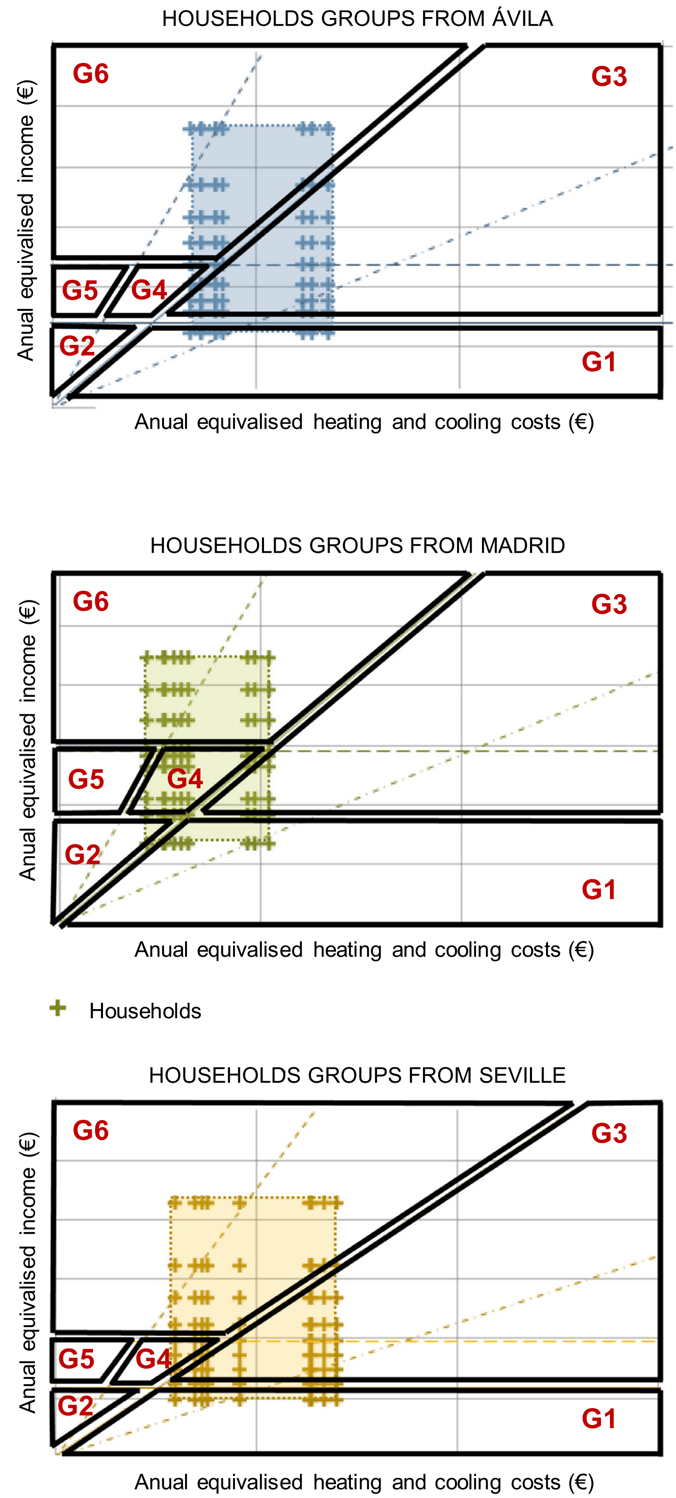

Fig. 10. Households division into groups according to fuel and monetary poverty thresholds.

the adaptive demand and taking into account that heating systems also vary according to climate zones, regional differences were also incorporated in heating and cooling expenditure calculations. In this way, dwellings located in cold regions where heating needs are higher, as Castile and Leon or Madrid, available systems use cheaper energy sources as gas, while dwellings located in zones with milder winters, as those located in Andalusia, tend to use heating systems that do not require any kind of installation and

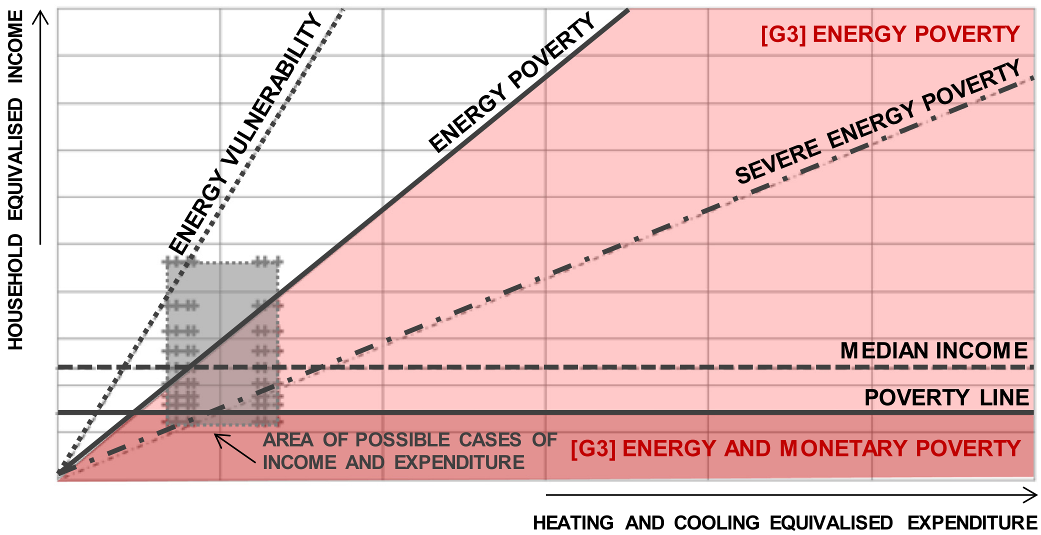

Fig. 11. Spanish households' energy poverty evaluation chart with energy retrofitting priority groups.

that use electricity as energy source. As a consequence of differences in available heating systems and thus in the energy source used, variations in energy prices affect households from diverse Regions in different ways and, hence, it makes some households more vulnerable than others to energy prices increase.

The concept defined as 'area of possible cases of income and expenditure' of a housing block represents different household situations regarding energy poverty that can be found within the same building block. The delimitation of this area enables to consider household probabilities to be suffering from energy poverty. The draft of the area of possible cases of income and expenditure showed important conclusions regarding energy retrofitting interventions. First find was that similar income households living in the same building block can be living under different energy poverty situations: some can be suffering from energy poverty and some others don't, only depending on the floor or the orientation of the dwelling. Second find was that in many cases, regardless household income decile level, the poor thermal habitability conditions of social housing plus the high energy prices lead a household into an energy poverty situation. Lastly, in buildings with a weak thermal enclosure, as studied ones, fuel and monetary poverty are closely related. In these cases, the intervention over the lowest income deciles is urgent.

The developed method is focused on indoor thermal comfort and subsequent energy needs related to heating and cooling and so is defined the energy poverty threshold. Main purpose of the research was to build a useful tool for energy retrofitting decision making processes where habitability conditions are crucial. The energy expenditure depends on climatic differences across regions: different energy needs due to differences in climatic solicitations, heating and cooling systems and energy sources utilised.

The 10% threshold initially adopted was revised in order to refer only to heating and cooling demand. That is why the distribution of household energy consumption was studied [70] and new thresholds were determined. Thus, for Castile and Leon and the Autonomous Region of Madrid this threshold was fixed in 3.5% of the income and in Andalusia in 4.4%. Then, the vulnerability threshold was fixed as half the energy poverty threshold and the severe energy poverty as the double. Future research should expand the evaluation of households' energy expenditure, incorporating the rest of energy needs related to dwellings such as hot water, cooking, electric appliances and lighting. Furthermore, a thorough study of Spanish housing stock and the energy required to attain minimal thermal habitability conditions should be conducted. This would lead to a reformulation of the 10% threshold towards a more accurate delimitation of the 'reasonable energy costs'.

The division of households into groups highlights some important particularities of energy poverty in Spain. First, for the three cases analysed, those households living under monetary poverty line also live under energy poverty conditions. Low income families tend to live in a non-efficient housing stock, so it is expectable to be a common situation in other cases. Second, it was found that, as expected, extreme winter conditions make households have important heating requirements that push them to an energy poverty situation. However, households from climates with milder conditions are in a surprising weak situation towards energy poverty due to the expensive energy source they use, despite having relative low heating requirements.

6. Conclusions

This research aimed to set a new method for evaluating households' energy poverty in the Spanish context that gathers climatic, socioeconomic and building particularities of the country. Spanish climatic variety and resulting energy needs among households is reflected in the method through the incorporation of adaptive thermal comfort criteria. Thus, the evaluation of required energy expenditure to achieve minimal indoor thermal habitability conditions differs according to climatic zone locations. Energy poverty and vulnerability thresholds defined as a fixed share of income required to cover households' heating and cooling energy expenditure also varies across regions. Existing socioeconomic differences among Spanish Autonomous Regions are gathered in the method with the inclusion of household equivalent income and monetary poverty threshold. Both concepts enable the comparison among different household life style standards and the measurement of inequalities in a society. Lastly, particularities regarding building characteristics are considered in the method. The utilisation of operative temperature in the energy evaluation enables a higher accuracy in the evaluation of thermal comfort and helps the inclusion of the building envelope thermal properties such as the presence of thermal inertia. Also, as building block is the most common building typology in Spain, the method reflects the relative position of households within the block which poses important differences in heating and cooling needs. This makes households

experience different energy poverty situation only depending on their relative position within the block.

The method developed represents a useful tool for the identification of the fuel poor so housing retrofitting priorities can be set. Furthermore, household group division proposed helps determining the type of energy retrofitting intervention required and hence, establishing some policy guidelines in order to tackle energy poverty. Households more in need (Group 1), located under monetary threshold and whose theoretical energy expenditure is higher than energy poverty threshold, require a refurbishment of their dwellings through passive strategies that improve habitability conditions. Previous research has demonstrated that these households cannot afford the required energy expenditure or even do not have any heating system [51,58]. These interventions should be granted by Government since the low income of these households impedes them from investing in the retrofitting woks their houses require. Furthermore, considering the low real expenditure registered in many of these households, they cannot benefit from after-refurbishing repayments usually derived from savings in energy bills. Another type of intervention can be posed for those households that form Group 3, who do not fall below monetary poverty threshold but whose excessive energy expenditure locates them under energy poverty baseline. These households can see their situation improved not only by the improvement of their dwellings thermal enclosure but also by the replacement of their heating and cooling systems by newer and more efficient ones. Energy retrofitting of these dwellings according to income levels could be enhanced by means of subsidies given that, in contrast to households previously described in Group 1, these households are likely to enjoy some repayments after refurbishment.

Acknowledgments

The authors would like to thank Prof Mike Davies from University College London (UCL) and Prof Paul Wilkinson from the London School of Hygiene and Tropical Medicine (LSHTM) for their initial comments on the research, as well as contributions of members of the Complex Built Environment Systems group (CBES) based at the Institute for Environmental Design and Engineering (IEDE), The Bartlett, UCL.

Funding

This research was partly funded by Technical University of Madrid 2012 Programme to perform short stays in foreign institutions.

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